Search for dark matter and new physics with long-lived and unconventional signatures

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Long-Lived Particles (LLPs)

LLPs are **predicted in many BSM physics scenarios in particular regions of the model phase space:**

- Particle decays mediated via heavy virtual mediators (e.g. **heavy neutral leptons**).
- Nearly mass degenerate states (e.g. **compressed SUSY**).
- Small couplings to SM particles (e.g. **dark mediators**).

As a consequence, searches need to be performed considering an extra parameter: the LLP lifetime, $c\tau$.

An LLP signal could manifest itself in different sub-detectors in unconventional ways!

- $c\tau$ is often treated as a ‘free parameter’.
- A plethora of LLP experimental signatures.

Figure credits: H.Russell [link]
Long-lived dark sector mediators

Dark matter can be explored via LLP dark sector mediators in regions of the BSM phase space where:

- Dark sector is feebly coupled to SM → mediators are LLPs.
- Dark matter is not directly accessible → no signal in mono-X searches.

A widely used benchmark model is Higgs rare decays to LLPs, $H \rightarrow XX$.
- $X$ is long-lived and can be spin-1 ($Z_D$), or spin-0 ($S$).

For $Z_D$ arXiv:1412.0018:
- The lifetime, $c\tau_{Z_D}$, is controlled by the kinetic mixing ($\epsilon$).
- The signal rate, $B(H \rightarrow Z_D Z_D)$, is controlled via $H-H_D$ mixing ($\kappa$).
- The experimental signature depends on $B(Z_D \rightarrow ff)$, $c\tau_{Z_D}$, and $m_{Z_D}$.
Different LLP properties (e.g., charge, decay products, $c\tau$...) lead to different experimental signatures that often require dedicated and unconventional searches.

Recent CMS results covered in this talk:

**LLPs decaying to leptons:**
- Displaced dimuons, NEW: EXO-21-006, EXO-20-014.
- Displaced $e\mu, \mu\mu, ee$ pairs, EXO-18-003.

**LLPs decaying to hadronic final states:**
- Hadronic showers in muon system, EXO-20-015.
- Displaced jets in association with Z boson, EXO-20-003.
Displaced dimuons: introduction

Generic search for LLPs decaying into displaced dimuons **within and beyond the tracker.**
- Data collected by **dedicated double muon triggers**, relying on muon system information alone.

Search uses 3 exclusive dimuon categories, **STA-STA**, **STA-TMS**, **TMS-TMS**, defined by two type of reconstructed muons:
- **STA**: muon system only.
- **TMS**: STA + tracker information.

Attempt to **associate STA to TMS muons.**
- Main handle to suppress collision SM backgrounds in **STA-** categories.
Displaced dimuons: background evaluation

**Transverse collinearity angle, |ΔΦ|:** angle \([0, \pi]\) between the transverse decay length, \(L_{xy}\) and the dimuon \(p_T^{\mu\mu}\) vectors.

**Signal clusters at small |ΔΦ|.**
|ΔΦ| < \(\pi/4\) and opposite sign dimuon (OS) as signal region (SR).

**Backgrounds:**
- **|ΔΦ| symmetric (‘DY-like’):** e.g. prompt muon pairs with large \(L_{xy}\), \(d_{xy}\) significance due to resolution tails.
  - \(→ |ΔΦ| > 3\pi/4\) and OS as DY control region (DY-CR).
- **|ΔΦ| asymmetric (‘QCD-like’):** e.g. mis-measured muons produced in decays of low-mass dimuon resonances such as non-prompt \(J/\psi \rightarrow \mu\mu\).
  - \(→ |ΔΦ| < \pi/4\) and SS as QCD-CR.

Backgrounds are evaluated using two ABCD methods:

- **CR to SR transfer factors**, \(R_{DY}\), \(R_{QCD}\), are evaluated in data (per category and signal region) in background enriched measurement regions.

**PV**: Primary vertex

**CV**: Dimuon vertex

\(m_{\mu\mu} > 10\) GeV

NEW: EXO-21-006
**Displaced dimuons: measurement regions**

<table>
<thead>
<tr>
<th>Measurement Region</th>
<th>$L_{xy}/\sigma(L_{xy})$</th>
<th>$\min(d_{xy}/\sigma(d_{xy}))$</th>
<th>Main handles to suppress background</th>
</tr>
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<tbody>
<tr>
<td>TMS-TMS</td>
<td>&gt; 6</td>
<td>In [6, 10, &gt;20] intervals.</td>
<td>TMS muon isolation and vertex $\chi^2$</td>
</tr>
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<td>&gt; 6</td>
<td>Associate STA to TMS muons and TMS muon isolation.</td>
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<tr>
<td>STA-STA</td>
<td>&gt; 6</td>
<td>No requirement</td>
<td>Associate STA to TMS muons and dimuon quality.</td>
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Typical values:
- $R_{DY} \sim 0.8$ (syst. unc: 15%-40%)
- $R_{QCD} \sim 1.0 - 2.0$ (syst. unc: 15%-30%)

Events failing these requirements are used to evaluate the CR to SR transfer factors, $R_{DY}, R_{QCD}$:
- e.g. $R_{DY}$ measurement region in STA-STA.

NEW: EXO-21-006
Displaced dimuons: validation regions

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Events failing these requirements are used to validate the background predictions.
- e.g. $2 < \min(d_{xy}/\sigma(d_{xy})) < 6$ validation region in TMS-TMS.

NEW: EXO-21-006

$E_{\mu\mu} > 10$ GeV
$|\Delta\phi| < \pi/4$
Displaced dimuons: signal region

<table>
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<tr>
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<th>( \frac{L_{xy}}{\sigma(L_{xy})} )</th>
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**NEW:** EXO-21-006

\( m_{\mu\mu} > 10 \text{ GeV} \) \( |\Delta\phi| < \pi/4 \)

Search for excess in \( m_{\mu\mu} \) distribution.

Search is optimized in each dimuon category separately.
Displaced dimuons: results

Results are interpreted in $H\rightarrow Z_D Z_D$.
- Each category reaches its best sensitivity at a different $c\tau$.
  - At small/large $c\tau$, the results are dominated by TMS-TMS and STA-STA respectively.

$B(H\rightarrow Z_D Z_D) < 10^{-3} - 10^{-4}$, depending on $(m_{ZD}, c\tau_{ZD})$:
- Best limits for all $c\tau$ except for $c\tau_{ZD} \sim 0.5 \text{ mm to } 20 \text{ cm}$ (depending on $m_{ZD}$), where the search is complemented by the scouting search (EXO-21-014, next slide).
- Results reinterpreted in the 2D $(m_{ZD}, c\tau)$ plane.

Search is sensitive to a broad class of signals:
- Results include interpretation for a generic $\phi \rightarrow XX$ production in wide range of $m_\phi$, $m_X$ and $c\tau_X$.
- Material for reinterpretations [here](#).
First long-lived search using scouting dataset in CMS.

- Data collected by high rate triggers and storing exclusively information reconstructed at HLT.
  - Events passing a double muon L1 trigger.

Signature is at least one displaced dimuon pair.

- Within pixel tracker ($l_{xy} < 11$ cm).
- $|d_{xy}|/\sigma(d_{xy}) > 2$, and $|d_{xy}| / (l_{xy} m_{\mu\mu} / p_{T\mu\mu}) > 0.1$.
- $\Delta \phi (p_{T\mu\mu}, l_{xy}) < 0.02$.
- Reject dimuons close to detector material, or compatible with pile-up.

Search for narrow resonance in $m_{\mu\mu}$ distribution in bins of transverse decay length ($l_{xy}$), $p_{T\mu\mu}$ and muon isolation.

- Background is evaluated using $m_{\mu\mu}$ side-band windows around the probed signal hypothesis.
Displaced dimuons with scouting: results

Results are interpreted in $H \rightarrow Z_D Z_D$.

- Mass intervals near SM resonances ($K_S$, $\rho/\omega$, $\phi$, $J/\psi$, $\Upsilon$) are excluded (gray bands).

![Graph showing limits for $B(H \rightarrow Z_D Z_D)$]

Most stringent limits to $B(H \rightarrow Z_D Z_D)$:

- At low mass.
  - Results include $B \rightarrow \phi X$ low mass interpretation for $m_\phi < 5$ GeV.

- At high mass for tracker lifetimes ($c\tau_{Z_D} \sim 0.5$ mm to ~20 cm, depending on the mass).

Material for reinterpretations, ref, HEPData.

- e.g. upper limits on the number of observed events, signal efficiencies, tabulated cut flow yields...
Displaced ee, e\mu, \mu\mu pairs

**Inclusive** search for displaced leptons.

- No requirements on lepton charges or presence of a common vertex.
- It includes displaced electrons.

Signature is at least two isolated displaced leptons

- \( p_T > 35 - 70 \text{ GeV} \) depending on the year/lepton.
  - Driven by trigger requirements.
- Signal region split by final state, in lepton \( p_T, d_{xy} \) bins starting at \( |d_{xy}| > 100 \mu m \).

Background arises from leptons produced in \( \tau \) and heavy flavor decays.

Results are interpreted in **several BSM scenarios** ([HEPData](#)):
RPV SUSY squarks, GMSB SUSY sleptons, \( H \rightarrow SS \) ...
Hadronic showers in muon endcap detector

Target hadronic LLP decays beyond the calorimeters.

- **Geometric acceptance**: 10-15% for $c\tau = 1-10$ m, and $m_S = 10-55$ GeV.

Signature:

- Cluster of hits with large multiplicity ($N_{\text{hits}}$) in muon endcap.
  - It includes cluster ID and timing (-5 ns < $t$ < 12.5 ns) cuts.
- Veto clusters matched to jets or muon showers.
- Events triggered by $E_{\text{T}}^{\text{miss}} > 200$ GeV.
  - $\Delta\phi (E_{\text{T}}^{\text{miss}}, \text{cluster}) < 0.75$.

Background from Long-lived SM hadrons produced in pile-up interactions.

- Evaluated using data obtained inverting the $\Delta\phi$ or $N_{\text{hits}}$ cuts.
- Validated using:
  - Out of time pile-up: $t < -5$ ns.
  - Events failing the cluster ID.
Results interpreted in context of $H \rightarrow SS; S \rightarrow bb, qq, \tau\tau$ final states (HEPData).

- Sensitivity independent of $m_S$, and slightly lower for $\tau\tau$ final states.
- Sensitivity dominated by geometrical acceptance and trigger efficiency.
- Most stringent limits at the largest lifetimes, $c\tau > 6, 20, 40$ m for $m_S = 7, 15, 40$ GeV.
In the low lifetime regime, EXO-20-015 (targeting ggH) is complemented by EXO-20-003 (targeting ZH) (HEPData), a search for $ZH; H \rightarrow SS; S \rightarrow qq$ and $bb$:

- Search requires two isolated prompt leptons compatible with $m_Z$ that are used to trigger the event.
- Tag at least two displaced jets using track level variables: PV compatibility, $d_{xy}$ sig, and emission angle.
- Search sensitivity is limited by the Higgs production rate, $\sigma(ggH)/\sigma(ZH) \sim 65$ and $B(Z \rightarrow ll) = 3\%$. 

![Graphical representation](image.png)
Wrapping up

Constraints on $\mathcal{B}(H \rightarrow XX)$ strongly depend on $c\tau$, $m_X$ and $\mathcal{B}(X \rightarrow ff)$.  

Displaced dimuons (overlaid from new EXO-21-006)  
$\mathcal{B}(X \rightarrow \mu\mu) = 0.13$, $m_X = 40$ GeV

Examples of areas for potential improvement (split by final state):

- In $X \rightarrow \mu\mu$ at $c\tau \gtrsim 1$ m.
- In $X \rightarrow ee$, especially at large $c\tau$.
- In $X \rightarrow qq$, $\tau\tau$ at $c\tau \lesssim 1$ m, especially at low $m_X$. 
LLPs appear in traditional BSM scenarios in different regions of the model phase space.

- CMS has an extensive search program for LLPs targeting a wide range of lifetime/mass/charge/final state.
  - Today, (selected) recent examples focusing on dark mediators.

### Summary and outlook

Field is in continuous R&D → CMS keeps pushing its exploration of uncharted BSM phase space with novel ideas (e.g. dedicated triggers, new search techniques...), and increased emphasis on model independence and reinterpretation material.

→ Exciting times ahead for LLP searches ←